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APPLICATION

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TITLE: CONVERTING SENSED SIGNALS

INVENTOR: CHRISTOPHER J. KEMP
CHRISTOPH P. MENZEL

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CONVERTING SENSED SIGNALS

Background

5 This invention relates generally to converting sensed signals, such as acceleration and pressure, to a desirable form of electrical signals.

10 Sensors, such as impact sensors, may be used in a variety of applications, such as automotive airbag systems to protect passengers during collisions. Impact sensors, for example, may employ a variety of sense elements, such as dual capacitive sense elements or single capacitive sense elements. Sensing circuits that interface with dual capacitive sense elements may be less vulnerable to noise such as electromagnetic interference noise or power supply noise, partly because of the differential nature of the sensing circuits. While such differential sensing circuits may be less susceptible to noise, they tend to be rather expensive.

20 A more cost efficient approach may be to use single-ended circuits, which typically interface with single capacitive sense elements. However, single-ended circuits generally tend to be more susceptible to noise.

Thus, there is a need for a cost efficient way that may be less susceptible to noise to convert sensed signals into a desirable form of electrical signals.

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Brief Description of the Drawings

The invention may be understood by reference to the following description taken in conjunction with the accompanying drawings, in which like reference numerals
10 identify like elements, and in which:

Figure 1 is a stylized block diagram of a restraint system in accordance with one embodiment of the present invention;
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Figure 2 is a schematic diagram of a sensing circuit that may be implemented in the restraint system of Figure 1, in one embodiment;

20 Figure 3 is a timing diagram showing clock signals used in the sensing circuit of Figure 2, in accordance with one embodiment of the present invention; and

25 Figure 4 is a graphical illustration of voltages and transitions of selected nodes of the sensing circuit of

Figure 2, in accordance with one embodiment of the present invention.

Detailed Description

5 Referring now to Figure 1, a stylized block diagram of a restraint system 10 is illustrated in accordance with one embodiment of the present invention. The restraint system 10 may be employed in an automobile, for example, to protect passengers during collisions. In one embodiment, 10 the restraint system 10 may automatically deploy an airbag in the event of an activation worthy impact event.

The restraint system 10 may include a control unit 15, a sensing circuit 20 and a deployment block 25. The 15 control unit 15 may be a processor, in one embodiment. The sensing block 20 may, in one embodiment, provide a pulse density signal that may be indicative of a sudden acceleration or deceleration, for example. Based on the output of the sensing circuit 20, the deployment block 25 20 may determine, in one embodiment, whether an activation worthy impact event has occurred that may require action, such as deployment of airbags. If an activation worthy impact event occurs, the deployment block 25 may provide an activation signal on line 30, in one embodiment.

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Referring now to Figure 2, a schematic diagram of one embodiment of the sensing circuit 20 of Figure 1 is illustrated. The use of the sensing circuit 20 may not be limited to the restraint system 10; rather, the sensing circuit 20 may be employed in any one of a variety of applications where converting sensed signals to other forms of electrical signals (e.g., digital signals) may be useful or desirable.

In one embodiment, the sensing circuit 20 includes an input block 217, a sensing block 220, and a converting block 225. As described in more detail below, the sensing circuit 20 converts an output signal from the sensing block 220 to a digital signal when pre-selected voltages are applied to the sensing block 220 and other nodes of the sensing circuit 20, in accordance with one embodiment of the present invention.

In one embodiment, two non-overlapping clocks, UN (unity) and INT (integrate), are used to clock the sensing circuit 20, as shown in Figure 3. In one embodiment, during the UN clock cycles, selected nodes of the sensing circuit 20 are set to a predefined level, such as to a V_{CM} voltage level, as shown in Figure 3. In one embodiment, the sensing circuit 20 is clocked starting with the UN clock. Figure 3 illustrates an output signal, OUT, which

is the output of the sensing circuit 20, as described below in more detail.

Referring again to Figure 2, although not so limited in the illustrated embodiment, the sensing block 220 includes two capacitors, C_A and C_B , connected at a common node. The upward arrow through capacitor C_A indicates that the C_A capacitance may increase in response to an input, which, in one embodiment, may represent acceleration. The term "acceleration," as utilized herein, may include deceleration, in one embodiment. The downward arrow through capacitor C_B indicates that the C_B capacitance may decrease in response to an input signal. In one embodiment, the sensing block 220, upon sensing acceleration, provides an output signal to the converting block 225. The sensing block 220, in one embodiment, has an input terminal 222 and two output terminals 224, 226. The input terminal 222, in one embodiment, is a common node to the C_A and C_B capacitors.

The converting block 225, in one embodiment, includes an integrator 228 coupled to a comparator 231, which may be further coupled to a latch 234. A differential operational amplifier (opamp) 237, along with feedback capacitors, C_{FN} and C_{FP} , forms the integrator 228, in the illustrated embodiment. In one embodiment, an applied direct current

(DC) voltage, V_{CM} , to the opamp 237 sets a common-mode level of the integrator 228. In one embodiment, the V_{CM} voltage may be one-fourth or one-third of the supply voltage, which, for example, may be 5 volts.

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In one embodiment, integrator 228 is configured in a manner such that input terminals 238, 241 of the integrator 228 are held essentially constant at the V_{CM} voltage level. In one embodiment, output terminals 246, 248 of the
10 integrator 228 are held essentially constant at the V_{CM} voltage level, during the UN clock cycle. The input terminals 238, 241 of the integrator 228, in one embodiment, are coupled to the respective output terminals 224, 226 of the sensing block 220. In one embodiment, one
15 or more bond wires may be used to connect the sensing block 220 to the integrator 228 of the converting block 225.

The feedback capacitor, C_{FN} , may be coupled between the output terminal 246 and the input terminal 238 of the
20 integrator 228. The feedback capacitor, C_{FP} , may be coupled between the output terminal 248 and the input terminal 241 of the integrator 228.

The integrator 228, in one embodiment, includes two
25 switches 252, 253. During the INT clock phase or cycle (see Figure 3), the switch 252 is in the "INT" (i.e., up)

position, and during the UN phase, the switch 252 is in the "UN" (i.e., down) position, in one embodiment. Similarly, during the INT phase, the switch 253 is in the "INT" position, and during the UN phase, the switch 253 is in the "UN" position, in one embodiment.

The output terminals 246, 248 of the integrator 228 are coupled to respective input terminals of the comparator 231. The comparator 231, in one embodiment, provides an output signal that is a digital "1" if the voltage difference between the output terminals 246, 248 of the integrator 228 is positive, and a digital "0" if it is negative. The differential output voltage (i.e., the voltage at the output terminal 246 minus the voltage at the output terminal 248) of the integrator 228 is denoted herein as V_{OD} .

The output of the comparator 231 is provided to the latch 234, in one embodiment. The latch 234 transfers a "0" or "1" at its input terminal to its output terminal on each falling edge of the INT clock phase (see Figure 3), in one embodiment. The output signal (OUT) of the latch 234 may be a digital bit stream that is fed back into the switches (discussed below) of the input block 217. In one embodiment, the output of the latch 234 is the output of the sensing circuit 20. The density of 1's in the OUT

signal may be an indication of the magnitude of the amplitude of the input signal to the sensing block 220. That is, if the OUT signal contains no 1's, for example, the input signal (e.g., acceleration) arriving at the
5 sensing block 220 may be at the low end of its range. If, on the other hand, the OUT signal contains all 1's, the input signal of the sensing block 220 may be at a high end of its range. An OUT signal containing 1's on roughly 50% of the clock cycles, for example, may represent that the
10 input signal to the sensing block 220 may be in the middle of the range.

In one embodiment, three reference voltages, V_{REF1} , V_{REF2} , and GROUND, are applied to the sensing circuit 20 at
15 various nodes through the input block 217. In one embodiment, V_{REF2} may be substantially equal to the supply voltage (not shown) of the sensing circuit 20. The supply voltage, for example, may be 5 volts in one instance. V_{REF1} in one embodiment may be approximately twenty percent of
20 V_{REF2} , thus, if V_{REF2} is 5 volts, then V_{REF1} may be 1 volt, for example.

The sensing circuit 20, in one embodiment, may be calibrated with calibration voltages, V_{CAL1} and V_{CAL2} . In
25 some instances, it may be difficult to fabricate the sensing block 220 with tight tolerances. As such, the

sensing circuit 20 may be calibrated by adjusting the V_{CAL1} and V_{CAL2} voltages during a calibration operation after the sensing circuit 20 is assembled. During calibration, V_{CAL1} and V_{CAL2} voltages may be set to values that bring the sensitivity and offset calibration parameters of the sensing circuit 20 within a desirable specification range. After calibration, the V_{CAL1} and V_{CAL2} voltages may remain fixed for the lifetime of the sensing circuit 20.

In one embodiment, a storage unit 235 of the sensing circuit 20 may store the voltages V_{CAL1} and V_{CAL2} in digital form. The storage unit 235 may be a non-volatile programmable memory, such as electrically erasable programmable read-only memory (EEPROM), fuse-blowing memory, or zener-zapping memory.

The input block 217 in the illustrated embodiment includes seven switches 270-276 that are operated by the UN, INT, and OUT digital signals, as shown in Figure 2. The switches 270-274 are connected to the node labeled "UN" when the UN signal is high (see Figure 3), and to the node labeled "INT" when the INT signal is high, in one embodiment. The switches 275-276 are connected to the top node (labeled "OUT=0") when the output of the sensing circuit 20 is low, and to the lower node (labeled "OUT=1")

when the output of the sensing circuit 20 is high, in one embodiment.

During the UN and INT clock phases, the switch 270 may
5 receive V_{CAL1} and V_{REF1} voltages, respectively. An output
terminal of the switch 270 is coupled to a first input
terminal of the switch 275, in one embodiment. During the
UN and INT clock phases, the switch 271 may receive V_{REF1} and
 V_{CAL2} voltages, respectively. In one embodiment, an output
10 terminal of the switch 271 is coupled to a second input
terminal of the switch 275. An output terminal of the
switch 275 is coupled to a node 240 of the sensing circuit
20, in one embodiment.

During the UN and INT clock phases, the switch 273 may
15 receive V_{REF1} and V_{CAL1} voltages, respectively. An output
terminal of the switch 273 is coupled to a first input
terminal of the switch 276, in one embodiment. During the
UN and INT clock phases, the switch 274 may receive V_{CAL2} and
20 V_{REF1} voltages, respectively. An output terminal of the
switch 274 is coupled to a second input terminal of the
switch 276, in one embodiment. An output terminal of the
switch 276 may be coupled to a node 242 of the sensing
circuit 20.

During the UN and INT clock phases, the switch 272 may be coupled to GROUND and V_{REF2} , respectively. Thus, during the UN clock phase, the input terminal 222 of the sensing block 220 is coupled to GROUND, in one embodiment. During the INT clock phase, the V_{REF2} voltage is applied, in one embodiment, to the input terminal 222 of the sensing block 220. In one embodiment, as can be seen in Figure 2, the same input signal (e.g., V_{REF2} or GROUND voltage level) is applied to the common input terminal 222 of the C_A and C_B capacitors of the sensing block 220.

In one embodiment, an input capacitor C_N is coupled between the node 240 and the input terminal 238 of the integrator 228, and an input capacitor C_P is coupled between the node 242 and the input terminal 241 of the integrator 228. The input capacitors, C_N and C_P , and the capacitors C_A and C_B , of the sensing block 220, in one embodiment, deliver charge to (or extract charge from) the feedback capacitors, C_{FN} and C_{FP} , of the integrator 228 during the INT clock phases, in response to the voltage changes at the nodes 240, 242 and at the input terminal 222 of the sensing block 220. The switches 270-274 may cause the voltage changes at the nodes 240, 242 and the input terminal 222 of the sensing block 220, when the switches 270-274 change from the UN position to INT position, for example.

5 The operation of the sensing circuit 20 is described below. During the UN clock phase, the opamp 237 is switched into unity-gain feedback configuration, which means that the voltages at input terminals 238, 242 and output terminals 246, 248 of the opamp 237 are at the level of the common-mode voltage, V_{CM} , in one embodiment. Also, in one embodiment, during the UN phase, the voltages on the nodes 240, 242 and the input terminal 222 of the sensing block 220 are driven to levels determined by the value of the OUT signal. The value of the OUT signal, in one embodiment, depends on the polarity of V_{OD} (the integrator's differential output voltage) at the end of the previous INT phase. In one embodiment, the UN phase should be of an adequate duration to allow the voltage levels in the sensing circuit 20 to settle to a static level. In one embodiment, the duration may be one microsecond.

20 When the UN clock phase ends, the switches 270-274 and 252-253 open, and then close to the INT phase connections, in one embodiment. During the INT clock phase, in one embodiment, the feedback capacitors C_{FN} and C_{FP} are connected around the opamp 237. In one embodiment, the C_{FN} and C_{FP} feedback capacitors may still have a stored voltage as a result of the integrated charge from previous INT phases.

As mentioned above, both the input capacitors (C_N and C_P) and the sense element capacitors (C_A and C_B) may deliver charge to (or extract charge from) the feedback capacitors (C_{FN} and C_{FP}) in response to the change in position of the switches 270-274. When some or all of the voltages settle to essentially static values at the end of the INT phase, the value of V_{OD} may have changed to a new value. If this new value is positive, then the OUT signal may be a "1" for the next clock cycle. If the new value is negative, then the OUT signal may be a "0" for the next clock cycle.

Providing the OUT signal to the switches 275-276 causes the output voltage (V_{OD}) of the integrator 228 to change (on the INT phase) in a direction that tends to cause the OUT signal to change states (e.g., from zero to one, or vice-versa), in one embodiment. In other words, if V_{OD} on a given clock cycle is positive, then on the next clock cycle it may be either less positive or negative. And if V_{OD} on a given clock cycle is negative, then on the next clock cycle it may be either less negative or positive.

In one embodiment, the value of $(C_A - C_B)$, which is the response of the sensing block differential capacitance to the input excitation, may affect the size of the charge packets delivered to the integrator 228 on each clock

cycle, and ultimately affect the fraction of the OUT signal clock cycles that deliver 1's. This fractional pulse density (FPD) is the value of the output signal of the sensing circuit 20, in one embodiment. The FPD, in one
5 embodiment, is defined as the number of clock periods per second having a high output value, divided by the clock frequency.

In one embodiment, during non-triggering events (e.g.,
10 no sudden change in acceleration, pressure, etc.), the output of the sensing circuit 20 may be a series of alternating ones and zeros. In the event of a triggering event (e.g., existence of sudden acceleration), there may be an increase in capacitance of capacitor C_A and a decrease
15 in capacitance of capacitor C_B within the sensing block 220, in one embodiment. This differential capacitance ($C_A - C_B$), in one embodiment, may cause the sensing circuit 20 to output more ones than zeros for a selected time interval.

Referring now to Figure 4, a graphical illustration of the voltage levels and transitions that may be applied to various nodes of the sensing circuit 20 is shown in one embodiment, for both values of the OUT signal. In one
20 embodiment, when the OUT signal is a "0," it is an indication that the value of the differential output
25 voltage at the end of the previous INT phase (e.g., V_{OD} [n-

1)) of the integrator 228 was less than zero. In one embodiment, for the nodes 222, 240, and 242 of the sensing circuit 20, the tails of the arrows represent voltage levels during the UN phase, while the arrowheads represent voltage levels during INT phase. In one embodiment, the actual voltage transitions may occur during the INT clock phase; voltages applied during the UN phase may be viewed, in one embodiment, as starting points for the voltage transitions.

As shown in Figure 4, if the OUT signal is "0," then on the present clock cycle the voltage on the node 242 may be driven to the level of V_{REF1} during the unity (UN) clock phase, and then may be driven to the level of V_{CAL1} (line 410) during the integrate (INT) clock phase. Similarly, the voltage on the node 240 may transition from V_{CAL1} to V_{REF1} (line 420) during the INT phase. These voltage transitions may be verified with reference to Figures 2 and 3, for example. When the OUT signal is "1," the voltage on the node 242 may transition from V_{CAL2} to V_{REF1} (line 435), while the voltage on the node 240 may transition from V_{REF1} to V_{CAL2} (line 440).

As can be seen with reference to Figure 4, in one embodiment, the voltage at the input terminal 222 of the sensing element 220 transitions from ground to V_{REF2} (lines

442, 445) on every clock cycle independent of the value of the OUT signal.

In one embodiment, applying the above described
5 selected voltages to the sensing circuit 20 may result in a desirable FPD transfer function, as shown in more detail below. The FPD of the sensing circuit 20 may be derived as follows:

10 During the clock cycles for which OUT=0, the charge delivered on the INT phase (or clock) to the node 241 (and eventually to the C_{FP} feedback capacitor) by the voltage transitions at the nodes 242 and 222 may be defined by equation (1) below:

15

$$Q_{LP} = C_P \left(\frac{1}{2} V_{DG} - \frac{1}{2} V_{DIF} \right) + C_A (V_{REF2}) \quad \text{Equation (1)}$$

where V_{DIF} represents the difference between the two calibration voltages (i.e., V_{CAL2} - V_{CAL1}) and V_{DG}/2 represents
20 the difference between the average of the two calibration voltages and V_{REF1} (i.e., $\frac{V_{DG}}{2} = \frac{V_{CAL1} + V_{CAL2}}{2} - V_{REF1}$).

During the clock cycles for which OUT=0, the charge extracted during the INT phase from the node 238 (and from

the C_{FN} feedback capacitor) by the voltage transitions on the nodes 240 and 222 may be defined by equation (2) below:

$$Q_{LN} = C_N \left(\frac{1}{2} V_{DG} - \frac{1}{2} V_{DIF} \right) - C_B (V_{REF2}) \quad (2)$$

5

The delivery and extraction of the above charges cause the output of the integrator 228 to change during the INT clock phase, as defined in equation (3) below:

$$\Delta V_{ODL} = \frac{C_P \left(\frac{1}{2} V_{DG} - \frac{1}{2} V_{DIF} \right) + C_A (V_{REF2})}{C_{FP}} + \frac{C_N \left(\frac{1}{2} V_{DG} - \frac{1}{2} V_{DIF} \right) - C_B (V_{REF2})}{C_{FN}} \quad (3)$$

where ΔV_{ODL} is the change in the integrator output voltage when the OUT signal is low.

15 Assuming that $C_P = C_N = C_{IN}$ and that $C_{FP} = C_{FN} = C_F$ in one embodiment, then equation (3) becomes:

$$\Delta V_{ODL} = \frac{(2C_{IN}) \left(\frac{1}{2} V_{DG} - \frac{1}{2} V_{DIF} \right) + (C_A - C_B) (V_{REF2})}{C_F} \quad (4)$$

During the clock cycles for which OUT=1, the output of the integrator 228 may be similarly determined, as shown in equation (5) below:

$$\Delta V_{ODH} = \frac{-(2C_{IN})\left(\frac{1}{2}V_{DG} + \frac{1}{2}V_{DIF}\right) + (C_A - C_B)(V_{REF2})}{C_F} \quad (5)$$

In one embodiment, the fractional pulse density may be related to the above output voltage changes by equation (6):

$$FPD = \frac{1}{1 - \frac{\Delta V_{ODH}}{\Delta V_{ODL}}} \quad (6)$$

Substituting equations (4) and (5) into equation (6), and then simplifying, yields equation (7) below:

$$FPD = \frac{1}{2} - \frac{1}{2} \frac{V_{DIF}}{V_{DG}} + \frac{V_{REF2}}{2V_{DG}C_{IN}}(C_A - C_B) \quad (7)$$

The FPD, based on equation (7), may be generalized as shown in Equation (8) below:

$$FPD = B + G[C_A - C_B] \quad (8)$$

$$\text{where } B = \frac{1}{2} - \frac{1}{2} \frac{V_{DIF}}{V_{DG}} \text{ and } G = \frac{V_{REF2}}{2V_{DG}C_{IN}}.$$

The equations (7) and (8), in one embodiment,
 5 illustrate how the sensing circuit 20 may be calibrated.
 The sensitivity calibration value may be adjusted by
 altering V_{DG} , which may entail raising or lowering both of
 the calibration voltages together, in one embodiment.
 Adjusting V_{DG} may increase or decrease "G" in equation (8).
 10 Upon setting the sensitivity value, the offset calibration
 value may be adjusted by changing V_{DIF} , which may entail
 raising or lowering the calibration voltages in opposite
 directions, in one embodiment. Altering V_{DIF} may increase
 or decrease "B" in equation (8).

15 One or more embodiments of the present invention may
 be cost efficient to produce and may also be less
 susceptible to noise. The cost savings may result since
 the sensing circuit 20 in one or more embodiments may
 20 employ a single sense element, which may be less expensive
 than dual sense elements. Additionally, one or more
 embodiments of the present invention may require fewer
 bondpads and/or wirebonds during manufacturing. In one
 embodiment, coarse calibration may be performed on the

sensing circuit 20 by adjusting the input capacitors, C_p and C_N , with a metal mask.

5 The particular embodiments disclosed above are
illustrative only, as the invention may be modified and
practiced in different but equivalent manners apparent to
those skilled in the art having the benefit of the
teachings herein. Furthermore, no limitations are intended
to the details of construction or design herein shown,
10 other than as described in the claims below. It is
therefore evident that the particular embodiments disclosed
above might be altered or modified and all such variations
are considered within the scope and spirit of the
invention. Accordingly, the protection sought herein is as
15 set forth in the claims below.